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A Preliminary Cost Minimization Analysis of FGD By-Product Management from the Power Plant Perspective

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Project: Land Application Uses For Dry FGD By-Products

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Acid rain has long been suspected in the deterioration of streams, lakes, forests, soils, and various fabricated structures. These resources are adversely effected by acidic precipitation linked to increased sulfur dioxide and nitrogen oxides emissions. Acid rain is formed when sulfur dioxide and nitrogen oxide react with other chemicals in the atmosphere (Helme and Neme, 1991). The primary source of sulfur dioxide and nitrogen oxide, as identified by the United States Environmental Protection Agency, is associated with the combustion of coal used in the production of electricity (Helme and Neme, 1991). The amount of sulfur dioxide produced depends upon the sulfur content of the coal being combusted. Coal higher in sulfur inevitable produce higher concentrations of sulfur dioxide and thus, precipitation which is more acidic.

The actual or potential degradation of resources by acid rain are vast. For example, in the Adirondack Mountains up to 15 percent of the medium to large lakes, those lakes greater than 10 acres, are chronically acidic due primarily to acid rain, and 25 percent of small lakes are likewise effected (Helme and Neme, 1991). The National Acid Precipitation Assessment Program (NAPAP) has estimated that nearly 20 percent of the nations lakes and streams have little or no acid-buffering capacity, thus are susceptible to current and future acidification.

Sulfur content of coal varies from state to state and region to region. Low sulfur Western coal generally has a sulfur content of about 0.5 percent, as compared with low sulfur coal from southern Appalachia which is about 1 percent sulfur. Coal from northern Appalachia and the lower midwestern states are about 2 - 3 percent sulfur. Western low sulfur coal accounts for about 40 percent of the coal sold to electric utilities, while southern Appalachia low sulfur coal commands about 20 percent of the utility market. The remaining market is captured by higher sulfur coal from northern Appalachia and lower midwestern states. Utility coal consumption has nearly doubled since the mid 1970's to more than 750 million tons annually, or about 85 percent of total coal consumption in the U.S.

The top ten producers of sulfur dioxide and nitrogen oxide emissions are shown in Table 1. SO_2 emissions are concentrated primarily along the Ohio River Valley. Forty-four percent of the U.S. SO_2 emissions are produced in this region by Ohio, Indiana, Pennsylvania, Illinois, West Virginia, with the inclusion of Missouri and Tennessee. In addition, four of the five highest SO_2 producers are also among the top ten NO_x producing states (EPA, 1986). Clearly, the Ohio River Valley is a major producer of emissions associated with acid rain, and significantly impacted by legislation mandating emission standards.

Table 1 Top Ten SO_2 and NO_x Producing States in 1984 (millions of tons)

		SO_2		NO_x
1	Ohio	2.58	Texas	3.25
2	Indiana	1.67	California	1.17
3	Pennsylvania	1.6	Ohio	1.14
4	Illinois	1.38	Illinois	0.99
5	Texas	1.24	Pennsylvania	0.92
6	Missouri	1.18	Indiana	0.83
7	West Virginia	1.02	Florida	0.70
8	Florida	0.99	Michigan	0.69
9	Georgia	0.93	Louisiana	0.68
10	Tennessee	0.92	New York	0.62

Source: EPA Journal, 1986

Emission Abatement Policy:

Title IV of the 1990 Clean Air Act addresses sulfur dioxide, nitrogen oxide, and particulate matter emissions associated with the burning of fossil fuels. This legislation mandates a 10 million ton (40 percent) reduction in the nations sulfur-dioxide emissions (based upon 1980 emission levels) by the year 2000, and a two million ton reduction in nitrogen oxide (Claussen, 1991).

The acid rain program developed by the EPA under this title sets a ceiling on sulfur dioxide emissions from electric power plants and allows individual utility companies to determine the most cost effective means of achieving these new mandates. Compliance is expected to be achieved through conservation efforts, using fuels lower in sulfur, purchasing of emission allowances, retrofitting existing plants with pollution control devices, and/or a combination of the above.

Currently the only pollution reduction technology which can be used on existing power plants to reduce SO_2 emissions to mandated levels is flue gas desulfurization (FGD). Through the use of a sorbent, such as limestone, exhaust gases are "scrubbed" of SO_2. One such process is referred to as a dry scrubber process. Other options are wet scrubbing. These FGD technologies are capable of reducing SO_2 emissions by as much as 95% from current power plant emissions (EPA, 1986). However, this process of "scrubbing" creates another environmental concern— disposal of the used sorbent. Table 2 shows the potential quantity of FGD by-product produced in Ohio if six of the 23 Ohio power plants convert to this dry scrubbing technology.

Not all power plants are expected to convert to dry injection technology. Of the 23 power plants identified in Ohio (Table 2), **potential** convertors to dry injection FGD technology by the year 2000 were estimated.

In this analysis, a least cost transportation model was developed depicting the least cost distribution of dry FGD by-product material from these potential electric power generating sites to numerous end use alternatives. The scenario assumes six power plants retrofit with this dry injection technology. This analysis is only preliminary since options regarding SO_2 emissions reduction at the plants are still being weighted.

Table 2 Sources of Dry FGD by-product by the year 2000

Company Name Plant Name	Probable Compliance Technology	Current Bottom Fly Ash Product (tons/year)	Potential Dry FGD By-Product (tons/year)
Toledo Edison Co. Bay Shore Plant	WS	95,000	0
Toledo Edison Co. Acme Plant	?	13,000	0
Cleveland Elec. Illum. Co. Ashtabula Plant	WS	108,000	0
Cleveland Elec. Illum. Co. Avon Lake Plant	WS	131,000	0
Cleveland Elec. Illum. Co. Eastlake Plant	WS	200,000	0
Cleveland Elec. Illum. Co. Lakeshore Plant	WS	17,000	0
Ohio Edison Co. Toronto Plant	?	39,000	0
Ohio Edison Co. W.H. Sammis Plant	DS	520,000	1,733,333
Ohio Edison Co. Niles Plant	DS	14,000	46,667
Ohio Edison Co. Gorge Plant	?	10,000	0
Ohio Edison Co. Edgewater Plant	DS	21,000	70,000
Ohio Edison Co. R.E. Burger Plant	DS	131,000	436,667
AMP-Ohio, Inc. Gorsuch Station	?	70,000	0

Table 2 (cont...) Sources of Dry FGD by-product by the year 2000

Company Name Plant Name	Probable Compliance Technology	Current Bottom Fly Ash Product (tons/year)	Potential Dry FGD By-Product (tons/year)
Ohio Power Co. Cardinal Plant	?	531,000	0
Ohio Power Co. Gavin Plant	WS	689,000	0
Ohio Power Co. Muskingum River Plant	DS	282,000	940,000
Ohio Valley Electric Corp. Kyger Creek Plant	FS	135,000	0
Cincinnati Gas & Electric W.C. Beckjord Station	?	115,000	0
Cincinnati Gas & Electric Miami Fort Station	WS	300,000	0
Columbus & Southern Power Conesville Plant	WS	120,000	0
Columbus & Southern Power Picway Plant	?	20,000	0
Dayton Power & Light J.M. Stuart Plant	?	780,000	0
Mead Paper Co. Mead Paper Co.	?	47,000	0
Zimmer Plant	WS	?	0
Appalachian Power Co. Mountaineer Plant	DS	265,000	883,333
Total		4,653,000	4,110,000

Key: WS= Wet scrubbing, fuel switch or other; DS= Dry scrubbing; ?=unkown
Source: prelimenary estimates by project personnel

Proposed uses of dry FGD by-product

Landfilling of this by-product material is the current means of disposal. However, it has been suggested that dry FGD by-product material has chemical properties which makes it valuable as an agricultural lime substitute, soil amendment in coal surface mine reclamation, and highway embankment construction material. This analysis focuses on dry FGD by-product use in agriculture land application, current coal surface mine reclamation, and landfilling.

Agricultural land application

FGD by-product has many characteristics similar to agricultural lime, and it is expected that dry FGD by-product materials could be a close substitute for agricultural lime. For this reason it is expected that agricultural lime sales would be a good proxy for estimating the quantity of FGD by-product demanded in each Ohio county. Table 3 shows the annual sales of agricultural lime by Ohio county. These estimates are based upon a five year average agricultural lime sales in each county. Since FGD by product has 60 percent the neutralizing potential of agricultural lime, agricultural lime sales were adjusted to estimate FGD by-product demand. That is, FGD by-product has a lower total neutralizing potential (TNP), thus higher application rates are necessary to achieve the same results as agricultural lime. The estimated quantity of FGD by-product demanded reflects these adjustments in TNP.

Table 3 Agricultural lime sales as proxy for dry FGD demand by Ohio county

County	1985	1986	1987	1988	1989	1990	Total 6 Yr	Avg. 6 Yr	Estimated Tons of Ag. Lime	Estimated FGD Demand (1.66 TNP) (25% adoption)
Adams	$12911.00	$9633.00	$19109.00	$14203.00	$22564.00	$18317.00	$96737.00	$16122.83	4030.71	6719.19
Allen	13705.00	7714.00	16250.00	11535.00	4286.00	19822.00	73312.00	12218.67	3054.67	5092.13
Ashland	33222.00	23046.00	30948.00	31637.00	32510.00	26914.00	178277.00	29712.83	7428.21	12382.82
Ashtabula	13403.00	7780.00	12841.00	10457.00	14124.00	22013.00	80618.00	13436.33	3359.08	5599.59
Athens	643.00	615.00	519.00	6733.00	4554.00	5045.00	18109.00	3018.17	754.54	1257.82
Auglaize	11987.00	8154.00	76477.00	10704.00	9766.00	8566.00	125654.00	20942.33	5235.58	8727.72
Belmont	15838.00	14192.00	17561.00	14113.00	6075.00	3088.00	70867.00	11811.17	2952.79	4922.30
Brown	15266.00	12159.00	23563.00	17364.00	11583.00	14001.00	93936.00	15656.00	3914.00	6524.64
Buttler	5269.00	1369.00	7777.00	8633.00	4280.00	1774.00	29102.00	4850.33	1212.58	2021.38
Carroll	4853.00	4385.00	2026.00	3538.00	7656.00	6931.00	29389.00	4898.17	1224.54	2041.31
Champaign	8056.00	6465.00	13724.00	10907.00	11621.00	7524.00	58297.00	9716.17	2429.04	4049.21
Clark	4277.00	7659.00	17588.00	7311.00	5575.00	3578.00	45988.00	7664.67	1916.17	3194.25
Clermont	7789.00	10837.00	15987.00	16354.00	6807.00	14190.00	71964.00	11994.00	2998.50	4998.50
Clinton	17466.00	15377.00	26856.00	18725.00	9885.00	12525.00	100834.00	16805.67	4201.42	7003.76
Columbiana	13934.00	13030.00	20800.00	18113.00	18344.00	14455.00	98676.00	16446.00	4111.50	6853.87
Coshocton	35937.00	25441.00	32588.00	25129.00	16276.00	26759.00	162130.00	27021.67	6755.42	11261.28
Crawford	13349.00	14203.00	20843.00	18098.00	19306.00	12940.00	98739.00	16456.50	4114.13	6858.25
Cuyahoga	8893.00	23918.00	2936.00	8888.00	10586.00	2219.00	57440.00	9573.33	2393.33	3989.69
Darke	20740.00	11634.00	23508.00	12307.00	12273.00	10113.00	90575.00	15095.83	3773.96	6291.19
Defiance	18770.00	26857.00	31904.00	31682.00	26509.00	22909.00	158631.00	26438.50	6609.63	11018.24
Delaware	36352.00	33098.00	23268.00	12996.00	15603.00	11144.00	132461.00	22076.83	5519.21	9200.52
Erie	13275.00	10390.00	17137.00	23939.00	16665.00	13428.00	94834.00	15805.67	3951.42	6587.01
Fairfield	20839.00	22830.00	27411.00	34087.00	9663.00	25192.00	140022.00	23337.00	5834.25	9725.69
Fayette	12019.00	11905.00	17364.00	14302.00	12513.00	12711.00	80814.00	13469.00	3367.25	5613.21
Franklin	1915.00	2123.00	3439.00	23693.00	2101.00	982.00	34253.00	5708.83	1427.21	2379.16
Fulton	19858.00	21326.00	23411.00	24062.00	27655.00	19107.00	135419.00	22569.83	5642.46	9405.98
Gallia	9043.00	9890.00	8242.00	11675.00	7390.00	10161.00	56401.00	9400.17	2350.04	3917.52
Geauga	812.00	870.00	147.00	1415.00	603.00	667.00	4514.00	752.33	188.08	313.53
Greene	8689.00	8525.00	12533.00	9557.00	9506.00	14956.00	63766.00	10627.67	2656.92	4429.08
Guernsey	9346.00	9687.00	6337.00	5525.00	2983.00	6826.00	40704.00	6784.00	1696.00	2827.23
Hamilton	1238.00	566.00	766.00	2196.00	2371.00	2047.00	9184.00	1530.67	382.67	637.91
Hancock	6993.00	9684.00	11645.00	7905.00	8270.00	7017.00	51514.00	8585.67	2146.42	3578.08
Hardin	16698.00	13421.00	32042.00	14463.00	20435.00	10314.00	107373.00	17895.50	4473.88	7457.95
Harrison	1259.00	728.00	631.00	264.00	67.00	3640.00	6589.00	1098.17	274.54	457.66
Henery	13000.00	12332.00	15865.00	13503.00	16798.00	11228.00	82726.00	13787.67	3446.92	5746.01
Highland	39268.00	32489.00	69344.00	31592.00	20049.00	23153.00	215895.00	35982.50	8995.63	14995.71
Hocking	1887.00	1275.00	1835.00	1651.00	34.00	502.00	7184.00	1197.33	299.33	498.99
Holmes	5751.00	4081.00	8092.00	10087.00	7144.00	11453.00	46608.00	7768.00	1942.00	3237.31
Huron	42903.00	39180.00	60441.00	36670.00	36720.00	28634.00	244548.00	40758.00	10189.50	16985.90
Jackson	93.00	211.00	130.00	276.00	409.00	457.00	1576.00	262.67	65.67	109.47
Jefferson	1907.00	4049.00	4016.00	2451.00	4261.00	3093.00	19777.00	3296.17	824.04	1373.68
Knox	21227.00	20400.00	25416.00	19542.00	19668.00	16334.00	122587.00	20431.17	5107.79	8514.69
Lake	692.00	3098.00	103.00	2164.00	66.00	16038.00	22161.00	3693.50	923.38	1539.27

Table 3 (cont..)

County	1985	1986	1987	1988	1989	1990	Total 6 Yr	Avg. 6 Yr	Estimated Tons of Ag. Lime	Estimated FGD Demand (1.66 TNP) (25% adoption)
Lawrence	1234.00	825.00	328.00	1107.00	773.00	0.00	4267.00	355.58	88.90	148.19
Licking	19708.00	19586.00	32788.00	34448.00	24458.00	24385.00	155373.00	12947.75	3236.94	5395.97
Logan	4973.00	3683.00	5699.00	5982.00	4350.00	4376.00	29063.00	2421.92	605.48	1009.33
Lorain	24674.00	17095.00	23347.00	22063.00	18976.00	16036.00	122191.00	10182.58	2545.65	4243.59
Lucas	14327.00	30045.00	37529.00	11580.00	30991.00	12900.00	137372.00	11447.67	2861.92	4770.82
Madison	4204.00	2569.00	2925.00	3581.00	2783.00	4455.00	20517.00	1709.75	427.44	712.54
Mahoning	13500.00	9781.00	13359.00	12157.00	9641.00	11775.00	70213.00	5851.08	1462.77	2438.44
Marion	7536.00	5510.00	13556.00	4833.00	17721.00	5659.00	54815.00	4567.92	1141.98	1903.68
Medina	25232.00	22817.00	29998.00	25376.00	19938.00	17156.00	140517.00	11709.75	2927.44	4880.04
Meigs	512.00	577.00	337.00	641.00	407.00	869.00	3343.00	278.58	69.65	116.10
Mercer	14692.00	8207.00	19802.00	13548.00	10905.00	5826.00	72980.00	6081.67	1520.42	2534.53
Miami	10148.00	7844.00	14403.00	12618.00	11497.00	8817.00	65327.00	5443.92	1360.98	2268.75
Monroe	1972.00	1967.00	2011.00	1865.00	1169.00	1673.00	10657.00	888.08	222.02	370.11
Montgomery	3735.00	3202.00	6195.00	978.00	1112.00	2376.00	17598.00	1466.50	366.63	611.16
Morgan	5087.00	3579.00	718.00	3090.00	556.00	5057.00	18087.00	1507.25	376.81	628.15
Morrow	4223.00	4443.00	8509.00	5615.00	4756.00	3220.00	30766.00	2563.83	640.96	1068.48
Muskingum	13787.00	22006.00	54255.00	22283.00	32876.00	17940.00	163147.00	13595.58	3398.90	5665.96
Noble	1525.00	1012.00	1946.00	2799.00	1812.00	2382.00	11476.00	956.33	239.08	398.55
Ottawa	28654.00	49527.00	23478.00	23481.00	26226.00	23451.00	174817.00	14568.08	3642.02	6071.25
Paulding	38113.00	26399.00	42347.00	30806.00	30248.00	9798.00	177711.00	14809.25	3702.31	6171.75
Perry	7778.00	11265.00	4824.00	3883.00	1289.00	6689.00	35728.00	2977.33	744.33	1240.80
Pickaway	10403.00	9339.00	23700.00	11966.00	11247.00	18204.00	84859.00	7071.58	1767.90	2947.08
Pike	25635.00	37.00	45016.00	36199.00	17687.00	21220.00	145794.00	12149.50	3037.38	5063.30
Portage	14643.00	10617.00	11400.00	12123.00	9857.00	41674.00	100314.00	8359.50	2089.88	3483.82
Preble	16753.00	7330.00	23221.00	8172.00	10404.00	10729.00	76609.00	6384.08	1596.02	2660.57
Putnam	6881.00	8666.00	12155.00	10595.00	17012.00	16727.00	72036.00	6003.00	1500.75	2501.75
Richland	19139.00	17890.00	22716.00	18169.00	17230.00	23476.00	118620.00	9885.00	2471.25	4119.57
Ross	3550.00	3321.00	12791.00	7388.00	7474.00	12412.00	46936.00	3911.33	977.83	1630.05
Sandusky	11794.00	8858.00	10034.00	9278.00	7085.00	39889.00	86938.00	7244.83	1811.21	3019.28
Scioto	777.00	2137.00	2283.00	1630.00	4061.00	2192.00	13080.00	1090.00	272.50	454.26
Seneca	29254.00	26326.00	39434.00	28176.00	29221.00	7209.00	159620.00	13301.67	3325.42	5543.47
Shelby	9312.00	5936.00	14852.00	9699.00	9679.00	7030.00	56508.00	4709.00	1177.25	1962.48
Stark	17477.00	13380.00	14494.00	9440.00	7319.00	6471.00	68581.00	5715.08	1428.77	2381.76
Summit	7818.00	7041.00	3685.00	4064.00	12144.00	9684.00	44436.00	3703.00	925.75	1543.23
Trumble	26222.00	18557.00	12964.00	16220.00	18994.00	17815.00	110772.00	9231.00	2307.75	3847.02
Tuscarawas	14313.00	16383.00	9695.00	9940.00	9838.00	17452.00	77621.00	6468.42	1617.10	2695.71
Union	4816.00	7540.00	20465.00	6543.00	10637.00	6094.00	56095.00	4674.58	1168.65	1948.13
Van Wert	8658.00	5001.00	4607.00	2977.00	8076.00	2791.00	32110.00	2675.83	668.96	1115.15
Vinton	1572.00	499.00	256.00	404.00	891.00	783.00	4405.00	367.08	91.77	152.98
Warren	7648.00	6504.00	14203.00	7794.00	5657.00	7742.00	49548.00	4129.00	1032.25	1720.76
Washington	13142.00	8855.00	9661.00	9271.00	4536.00	11080.00	56545.00	4712.08	1178.02	1963.76
Wayne	54898.00	55471.00	69635.00	50987.00	50455.00	48666.00	330112.00	27509.33	6877.33	11464.51
Williams	25959.00	26107.00	28232.00	32667.00	38356.00	33145.00	184466.00	15372.17	3843.04	6406.35
Wood	75838.00	20434.00	26240.00	33202.00	29507.00	17030.00	202251.00	16854.25	4213.56	7024.01
Wyandot	20804.00	23945.00	29263.00	11446.00	13443.00	11004.00	109905.00	13738.13	3434.53	5725.36
Unkown				867.00	5221.00		6088.00	3044.00	761.00	1268.59
Total	1234292.00	1078739.00	1582776.00	1192397.00	1104069.00	1078126.00	7270399.00	898287.38	224571.84	374361.26

Source: Ohio Agriculture Statistics

Transportation of the FGD by-product is expected to be similar to that of agricultural lime. Only slight modification of existing equipment is necessary to transport the by-product from the source (power plant) to the destination (farm, coal mine or landfill), and to apply the by-product to agricultural land. Under these assumptions, FGD by-product is expected to be back hauled from the power plant to various locations throughout the state by trucks. Once the by-product has reached the farm it is expected that conventional lime spreaders will apply this by-product to agricultural lands.

Strip/Surface Coal Mine Reclamation

Coal surface mine operations are required to reclaim lands which have been mined. During the reclamation phase lime is often used to return the mined spoils back to a pH level conducive to plant growth. It is expected that FGD by-product materials can also be used for this same purpose.

Table 4 shows the estimated quantity of FGD by-product material demanded to meet current strip mine reclamation work. These estimates are derived from data reporting tons of coal sold in each Ohio coal mining county (1989). From these estimates an average number of tons per acre of coal extraction were used to estimate the number of acres displaced by surface coal mining in a given year. Based upon the estimated number of surface acres mined and an application rate of 20 tons per acre, an estimate for the quantity of FGD by-product demanded can be determined. Note, the application rate is that which is expected to be used in experimental field work.

Table 4 Estimated number of coal surface mine acres by Ohio County (1989)

County	Tons of Coal Mined Annually by Ohio County	Estimated Acres Mined Annually	Estimated tons of dry FGD by-product used at 20 tons/acre	Tons of dry FGD by-product (25% adoption)
Athens	151,021	62	1,247	312
Belmont	2,697,023	1,113	22,262	5,565
Carroll	793,097	327	6,546	1,637
Columbiana	614,528	254	5,072	1,268
Coshocton	1,891,950	781	15,617	3,904
Guernsey	139,065	57	1,148	287
Harrison	2,065,225	852	17,047	4,262
Hocking	126,965	52	1,048	262
Holmes	452,349	187	3,734	933
Jackson	992,849	410	8,195	2,049
Jefferson	1,915,949	791	15,815	3,954
Lawrence	26,532	11	219	55
Mahoning	198,159	82	1,636	409
Muskingum	900,320	372	7,431	1,858
Noble	3,352,038	1,383	27,668	6,917
Perry	407,559	168	3,364	841
Stark	195,720	81	1,616	404
Tuscarawas	2,104,535	869	17,371	4,343
Vinton	1,476,756	609	12,189	3,047
Washington	65,382	27	540	135
Wayne	31,910	13	263	66
Total	20,598,932	8,501	170,028	42,508

The final end use alternative identified is that of landfilling. It is expected that FGD by-product will be landfilled in the event that the available quantity of the product is larger than its economical use in agricultural and/or coal surface mine reclamation. It is further assumed that landfilling is not constrained in the quantity of the by-product that can be accepted, and that landfills are in close proximity to the power plants or sources of FGD by-products.

Objectives of this research

The objectives of this research are (1) to develop a model to identify the least cost disposal methods of FGD by-product among the three stated alternative end uses from the producer or power plants perspective, (2) estimate the quantity of by-product used in each alternative, and (3) estimate the shadow price associated with each alternative end use. This particular component of the research does not address the social amenities/disamenities associated with FGD by-product disposal. For example, deterioration of roads and bridges from increased traffic, property value gain/loss from landfill activities, strip mine reclamation, abandon mine land reclamation, increased/ decreased ground and/or surface water quality from surface mine reclamation and abandon mine land reclamation, or landfilling activities, etc. However, work is in progress to quantify these amenities/disamenities. Once quantified the least cost disposal model can be re-estimated with the appropriate increase/decrease in cost associated with the given end use alternative. That is, the model can be modified to consider the social gain/loss associated with each end use alternative. Thereby providing a least cost disposal model which captures both a private and social accounting stance.

Model Development

Minimizing the total cost of transporting a product from some production point to various destination or demand points can be done through a series of linear equations. This type of least cost mathematical modeling, or transportation modeling, has been applied to the distribution of FGD by-product material to various destinations throughout Ohio. This least cost transportation model is based upon six source nodes (power plants) associated with the production of dry FGD by-product materials and its use as a substitute for agricultural lime in 88 Ohio counties, and a soil amendment at 21 Ohio coal surface mine reclamation sites, and six landfill sites located in proximity of the power plant.

To formulate this model mathematically, the following terms are defined.

a_i = the number of tons of FGD by-product material available at the power plant or source i, $i=1,2,\ldots,m$;

b_j = maximum number of tons of by-product required at each destination or alternative use (e.g. county for agricultural lime, reclamation site, or landfill), $j = 1,2,\ldots n$;

c_{ij} = unit transportation and application cost from each source i to each destination j, ($i = 1,2,\ldots,m$; $j = 1,2,\ldots,n$).

Assuming:

$\Sigma a_i = \Sigma b_j$; the quantity of FGD by-product available at source i must be equal to the demand for FGD by-product material in alternative end uses (including landfilling options).

$a_i > 0$; supply of by-product at each source node is positive.

$b_j > 0$; demand for by-product at each demand node is positive.

The problem then becomes determining the amount of FGD by-product material shipped to each of these alternative end uses, given that the cost of distribution and application of the by-product is known or can be estimated. Thus, the decision variable, x_{ij}, equals the number of tons of by-product material shipped from each source i to each destination j annually given some cost per unit shipped.

The transportation model estimated is:

$$Minimum\ Cost = \sum_{i}^{N} \sum_{j}^{N} c_{ij}\, x_{ij} \tag{1}$$

subject to:

$$\Sigma x_{ij} = a_i \quad (i = 1,2,...,m); \tag{2}$$

$$\Sigma x_{ij} \leq b_j \quad (j = 1,2,...,n); \tag{3}$$

$$x_{ij} \geq 0 \qquad (i = 1,2,...,m;\ j = 1,2,...,n). \tag{4}$$

Equation (1) represents the minimization of total distribution costs, assuming a linear cost structure for shipping, processing, and application of the dry FGD by-product material. Equation (2) shows that the quantity of by-product shipped from each source i to each alternative end use destination j must be equal to the quantity of by-product material available at source a_i. Equation (3) states that the quantity of by-product shipped from each source i to each destination j, must be less than or equal to the maximum quantity of by-product demanded at that destination. Finally, equation (4) indicates that the quantity of by-product shipped from each source i to each destination j can not be less than zero tons.

Data used for estimating the transportation model using six power plants:

All estimates pertaining to the quantity of dry FGD by-product demanded at various demand nodes for the two end use alternatives (agricultural and surface coal mine reclamation uses) have been adjusted for a 25 percent rate of adoption. It is expected that not all individuals using agricultural lime or reclaiming surface coal mines will completely adopt this new technology. Thus, the model uses a conservative or lower rate of adoption. However, it is important to note that the model can be re-run at various levels of adoption.

Linear distances from the power plant or source of dry FGD by-product to the center of each county were estimated. Table 5 shows these linear distances estimates for each Ohio county. Each column corresponds to a given power plant, while individual rows corresponds to individual counties. Each end use alternative is identified starting with agricultural land application followed by surface coal mine reclamation. The final row is the distance from the power plant to the landfill.

Once these distances have been determined, cost associated with moving the specified distance were estimated. In the case of agricultural land application, cost estimates were derived from the agricultural lime industry. It is expected that the dry FGD by-product will be transported in much the same manner as current agricultural lime. Thus, an estimate of $0.10 per ton per mile was used. In addition to moving the product from the source to the destination an application expense is incurred. Again, the application of the dry FGD by-product is expected to be similar to agricultural lime, which has an estimated application charge of $3.50 per ton. This expense includes the spreader and mechanism to load the product from a pile onto the spreader. Therefore, transportation costs were calculated at $0.10 per ton per mile, then an additional $3.50 per ton was added to each for expected application costs. Table 6 shows the estimated costs per ton of product distributed by source and destination.

Transportation of the dry FGD by-product to coal surface mine reclamation sites is also expected to cost $0.10 per ton per mile. Application of the dry FGD by-product is expected to be at significantly higher levels, potentially 20 tons per acre, than application rates associated with agricultural use. Thus, different equipment is expected to be used in distributing the by-product (e.g. a bulldozer or equivalent type of reclamation machinery), but application costs would not vary significantly and were estimated at $3.50 per ton.

Cost estimates for landfilling were obtained from interviews with representatives of electric utilities. All landfilling activities are regulated. Because dry FGD by-product material has a relatively high pH EPA requires that more stringent landfilling requirements must be met. Electric power plants have estimated that it would cost about $27.50 per ton of material to landfill dry FGD waste and meet current EPA guidelines.

Table 5 Estimated linear miles from source (power plant) to destination (county) for various dry FGD by-product disposal alternatives.

Agricultural Destination

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12
Adams	60.00	206.63	120.83	230.41	183.83	160.31
Allen	168.68	135.77	171.33	182.63	183.71	178.16
Ashland	148.00	48.41	110.02	87.32	91.92	95.27
Ashtabula	219.92	51.08	158.32	23.19	93.34	118.04
Athens	40.85	148.76	37.00	158.90	102.59	77.34
Auglaize	158.52	144.46	166.82	189.74	185.27	177.49
Belmont	114.98	107.42	44.94	95.19	27.31	0.00
Brown	83.02	219.35	142.80	246.56	203.59	180.97
Buttler	130.30	209.42	173.14	246.59	219.46	202.07
Carroll	143.56	67.74	79.43	57.01	25.00	41.00
Champaign	122.67	144.05	136.93	183.58	166.21	154.08
Clark	111.04	154.86	132.77	191.93	168.88	154.39
Clermont	100.84	216.40	154.50	247.59	210.30	189.48
Clinton	89.89	182.00	130.31	213.93	180.02	161.01
Columbiana	165.34	68.25	98.68	40.11	30.07	55.73
Coshocton	109.44	79.31	63.07	95.00	62.29	54.42
Crawford	146.76	76.28	124.65	119.87	121.75	120.31
Cuyahoga	188.40	0.00	137.46	50.09	91.40	107.42
Darke	155.80	180.76	180.21	223.89	210.95	199.06
Defiance	214.11	149.21	212.00	199.06	214.11	212.95
Delaware	108.78	105.42	100.17	140.09	120.42	110.03
Erie	183.79	47.10	148.92	97.00	123.71	131.55
Fairfield	68.88	127.58	68.15	150.57	110.98	92.42
Fayette	78.10	163.08	110.00	193.10	158.09	139.28
Franklin	88.14	125.40	92.03	155.88	126.38	111.29
Fulton	220.93	130.46	210.02	180.54	203.18	205.32
Gallia	0.00	188.40	70.71	199.72	141.40	114.98
Geauga	201.24	27.89	143.17	25.08	84.76	106.37
Greene	102.42	169.25	133.38	204.20	176.16	159.48
Guernsey	101.07	97.32	40.20	99.02	45.28	28.07
Hamilton	122.18	221.52	172.13	256.12	223.89	204.60
Hancock	169.52	108.16	160.43	155.91	162.98	160.73
Hardin	149.48	115.88	146.44	160.65	158.03	152.20
Harrison	127.09	86.33	60.44	76.12	18.68	21.19
Henery	201.76	125.26	193.41	175.07	191.38	191.47
Highland	73.68	191.23	123.00	219.32	179.23	157.99
Hocking	48.84	143.41	59.03	161.70	114.28	92.14
Holmes	127.58	60.83	81.71	82.76	66.29	66.03
Huron	166.87	51.08	133.96	98.48	114.95	119.85
Jackson	19.85	178.76	74.79	194.74	141.42	116.39
Jefferson	141.40	91.40	72.07	70.18	0.00	27.31
Knox	110.16	84.10	82.07	112.81	91.05	82.97
Lake	214.65	31.83	158.03	36.80	100.24	121.82
Lawrence	19.65	207.97	88.24	219.16	159.76	133.00
Licking	92.44	101.77	72.42	127.29	96.32	83.10
Logan	135.09	130.67	140.89	172.72	162.01	152.74
Lorain	176.14	25.08	133.14	73.33	100.26	110.60

Table 5 (cont...)
Agricultural Destinations

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12
Lucas	216.41	106.37	197.57	156.28	183.58	188.22
Madison	95.00	140.25	110.11	173.83	146.74	131.55
Mahoning	181.14	58.60	115.80	22.20	48.04	73.55
Marion	131.67	99.49	121.40	140.46	132.38	125.96
Medina	168.58	20.25	120.07	59.20	82.22	94.03
Meigs	26.25	166.51	44.60	174.75	115.21	88.73
Mercer	175.37	167.31	189.62	213.60	210.24	202.05
Miami	137.00	166.82	159.59	207.97	191.64	179.00
Monroe	94.05	125.57	23.35	117.72	50.33	23.09
Montgomery	125.72	182.12	157.81	220.59	197.67	182.33
Morgan	65.80	126.04	25.08	133.93	78.57	54.71
Morrow	125.72	84.29	105.38	121.80	111.45	105.95
Muskingum	88.29	100.50	46.86	114.06	70.38	54.04
Noble	83.22	116.97	20.62	118.30	58.73	34.13
Ottawa	199.37	80.31	174.50	130.38	156.92	162.48
Paulding	206.60	154.30	208.29	203.71	214.65	211.88
Perry	75.33	113.36	49.74	130.36	86.76	68.25
Pickaway	68.26	144.01	86.37	170.53	132.91	114.02
Pike	43.08	183.85	96.21	205.64	158.22	134.83
Portage	181.20	30.41	122.20	25.50	65.31	85.70
Preble	139.98	197.87	175.48	237.54	215.87	200.56
Putnam	185.40	130.05	182.41	178.76	187.48	184.77
Richland	140.70	63.66	110.44	103.37	102.62	102.22
Ross	50.21	163.48	86.15	186.64	142.58	120.77
Sandusky	185.54	75.24	161.01	125.04	146.25	150.42
Scioto	33.00	196.38	96.90	215.08	163.38	138.54
Seneca	172.53	79.56	151.21	128.13	142.24	143.96
Shelby	147.11	154.35	161.99	197.62	187.13	176.92
Stark	155.32	46.14	96.05	45.80	45.97	61.68
Summit	172.70	20.59	118.42	42.72	71.06	86.93
Trumble	199.72	50.09	136.34	0.00	70.18	95.19
Tuscarawas	126.29	69.63	68.18	73.82	40.31	41.73
Union	120.35	118.19	120.77	157.16	142.17	132.23
Van Wert	188.62	158.93	196.41	206.90	210.15	204.53
Vinton	31.58	159.13	59.14	174.64	122.49	98.23
Warren	107.15	194.08	149.27	228.48	197.59	179.27
Washington	70.71	137.46	0.00	136.34	72.07	44.94
Wayne	147.65	40.79	100.00	68.80	71.12	77.90
Williams	229.40	154.16	225.22	204.24	223.79	224.12
Wood	194.24	103.17	178.97	153.03	171.62	173.42
Wyandot	152.51	93.48	138.77	138.88	141.22	138.40

Table 5 (cont...)

Coal Surface Mine Reclamation and Landfilling Destinations

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12
Athens	40.85	148.76	37.00	158.90	102.59	77.34
Belmont	114.98	107.42	44.94	95.19	27.31	0.00
Carroll	143.56	67.74	79.43	57.01	25.00	41.00
Columbiana	165.34	68.25	98.68	40.11	30.07	55.73
Coshocton	109.44	79.31	63.07	95.00	62.29	54.42
Guernsey	101.07	97.32	40.20	99.02	45.28	28.07
Harrison	127.09	86.33	60.44	76.12	18.68	21.19
Hocking	48.84	143.41	59.03	161.70	114.28	92.14
Holmes	127.58	60.83	81.71	82.76	66.29	66.03
Jackson	19.85	178.76	74.79	194.74	141.42	116.39
Jefferson	141.40	91.40	72.07	70.18	0.00	27.31
Lawrence	19.65	207.97	88.24	219.16	159.76	133.00
Mahoning	181.14	58.60	115.80	22.20	48.04	73.55
Muskingum	88.29	100.50	46.86	114.06	70.38	54.04
Noble	83.22	116.97	20.62	118.30	58.73	34.13
Perry	75.33	113.36	49.74	130.36	86.76	68.25
Stark	155.32	46.14	96.05	45.80	45.97	61.68
Tuscarawas	126.29	69.63	68.18	73.82	40.31	41.73
Vinton	31.58	159.13	59.14	174.64	122.49	98.23
Washington	70.71	137.46	0.00	136.34	72.07	44.94
Wayne	147.65	40.79	100.00	68.80	71.12	77.90
Landfill	1.00	1.00	1.00	1.00	1.00	1.00

Table 6 Estimated cost of transporting dry FGD by-product to various destinations, assuming $0.10/ton/mile + $3.50 ton application costs and linear distances.

Agriculture Destinations

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12
Adams	9.50	24.16	15.58	26.54	21.88	19.53
Allen	20.37	17.08	20.63	21.76	21.87	21.32
Ashland	18.30	8.34	14.50	12.23	12.69	13.03
Ashtabula	25.49	8.61	19.33	5.82	12.83	15.30
Athens	7.59	18.38	7.20	19.39	13.76	11.23
Auglaize	19.35	17.95	20.18	22.47	22.03	21.25
Belmont	15.00	14.24	7.99	13.02	6.23	3.50
Brown	11.80	25.43	17.78	28.16	23.86	21.60
Buttler	16.53	24.44	20.81	28.16	25.45	23.71
Carroll	17.86	10.27	11.44	9.20	6.00	7.60
Champaign	15.77	17.90	17.19	21.86	20.12	18.91
Clark	14.60	18.99	16.78	22.69	20.39	18.94
Clermont	13.58	25.14	18.95	28.26	24.53	22.45
Clinton	12.49	21.70	16.53	24.89	21.50	19.60
Columbiana	20.03	10.32	13.37	7.51	6.51	9.07
Coshocton	14.44	11.43	9.81	13.00	9.73	8.94
Crawford	18.18	11.13	15.97	15.49	15.68	15.53
Cuyahoga	22.34	3.50	17.25	8.51	12.64	14.24
Darke	19.08	21.58	21.52	25.89	24.60	23.41
Defiance	24.91	18.42	24.70	23.41	24.91	24.80
Delaware	14.38	14.04	13.52	17.51	15.54	14.50
Erie	21.88	8.21	18.39	13.20	15.87	16.66
Fairfield	10.39	16.26	10.32	18.56	14.60	12.74
Fayette	11.31	19.81	14.50	22.81	19.31	17.43
Franklin	12.31	16.04	12.70	19.09	16.14	14.63
Fulton	25.59	16.55	24.50	21.55	23.82	24.03
Gallia	3.50	22.34	10.57	23.47	17.64	15.00
Geauga	23.62	6.29	17.82	6.01	11.98	14.14
Greene	13.74	20.42	16.84	23.92	21.12	19.45
Guernsey	13.61	13.23	7.52	13.40	8.03	6.31
Hamilton	15.72	25.65	20.71	29.11	25.89	23.96
Hancock	20.45	14.32	19.54	19.09	19.80	19.57
Hardin	18.45	15.09	18.14	19.56	19.30	18.72
Harrison	16.21	12.13	9.54	11.11	5.37	5.62
Henery	23.68	16.03	22.84	21.01	22.64	22.65
Highland	10.87	22.62	15.80	25.43	21.42	19.30
Hocking	8.38	17.84	9.40	19.67	14.93	12.71
Holmes	16.26	9.58	11.67	11.78	10.13	10.10
Huron	20.19	8.61	16.90	13.35	14.99	15.49
Jackson	5.48	21.38	10.98	22.97	17.64	15.14
Jefferson	17.64	12.64	10.71	10.52	3.50	6.23
Knox	14.52	11.91	11.71	14.78	12.60	11.80
Lake	24.96	6.68	19.30	7.18	13.52	15.68
Lawrence	5.46	24.30	12.32	25.42	19.48	16.80
Licking	12.74	13.68	10.74	16.23	13.13	11.81
Logan	17.01	16.57	17.59	20.77	19.70	18.77

Table 6 (cont...)

Agriculture Destinations

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12
Lorain	21.11	6.01	16.81	10.83	13.53	14.56
Lucas	25.14	14.14	23.26	19.13	21.86	22.32
Madison	13.00	17.52	14.51	20.88	18.17	16.65
Mahoning	21.61	9.36	15.08	5.72	8.30	10.86
Marion	16.67	13.45	15.64	17.55	16.74	16.10
Medina	20.36	5.52	15.51	9.42	11.72	12.90
Meigs	6.12	20.15	7.96	20.98	15.02	12.37
Mercer	21.04	20.23	22.46	24.86	24.52	23.71
Miami	17.20	20.18	19.46	24.30	22.66	21.40
Monroe	12.90	16.06	5.83	15.27	8.53	5.81
Montgomery	16.07	21.71	19.28	25.56	23.27	21.73
Morgan	10.08	16.10	6.01	16.89	11.36	8.97
Morrow	16.07	11.93	14.04	15.68	14.64	14.09
Muskingum	12.33	13.55	8.19	14.91	10.54	8.90
Noble	11.82	15.20	5.56	15.33	9.37	6.91
Ottawa	23.44	11.53	20.95	16.54	19.19	19.75
Paulding	24.16	18.93	24.33	23.87	24.96	24.69
Perry	11.03	14.84	8.47	16.54	12.18	10.32
Pickaway	10.33	17.90	12.14	20.55	16.79	14.90
Pike	7.81	21.88	13.12	24.06	19.32	16.98
Portage	21.62	6.54	15.72	6.05	10.03	12.07
Preble	17.50	23.29	21.05	27.25	25.09	23.56
Putnam	22.04	16.50	21.74	21.38	22.25	21.98
Richland	17.57	9.87	14.54	13.84	13.76	13.72
Ross	8.52	19.85	12.11	22.16	17.76	15.58
Sandusky	22.05	11.02	19.60	16.00	18.12	18.54
Scioto	6.80	23.14	13.19	25.01	19.84	17.35
Seneca	20.75	11.46	18.62	16.31	17.72	17.90
Shelby	18.21	18.94	19.70	23.26	22.21	21.19
Stark	19.03	8.11	13.10	8.08	8.10	9.67
Summit	20.77	5.56	15.34	7.77	10.61	12.19
Trumble	23.47	8.51	17.13	3.50	10.52	13.02
Tuscarawas	16.13	10.46	10.32	10.88	7.53	7.67
Union	15.54	15.32	15.58	19.22	17.72	16.72
Van Wert	22.36	19.39	23.14	24.19	24.52	23.95
Vinton	6.66	19.41	9.41	20.96	15.75	13.32
Warren	14.22	22.91	18.43	26.35	23.26	21.43
Washington	10.57	17.25	3.50	17.13	10.71	7.99
Wayne	18.26	7.58	13.50	10.38	10.61	11.29
Williams	26.44	18.92	26.02	23.92	25.88	25.91
Wood	22.92	13.82	21.40	18.80	20.66	20.84
Wyandot	18.75	12.85	17.38	17.39	17.62	17.34

Table 6 (cont...)

Coal surface mine reclamation and landfill alternatives

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12
Athens	7.59	18.38	7.20	19.39	13.76	11.23
Belmont	15.00	14.24	7.99	13.02	6.23	3.50
Carroll	17.86	10.27	11.44	9.20	6.00	7.60
Columbiana	20.03	10.32	13.37	7.51	6.51	9.07
Coshocton	14.44	11.43	9.81	13.00	9.73	8.94
Guernsey	13.61	13.23	7.52	13.40	8.03	6.31
Harrison	16.21	12.13	9.54	11.11	5.37	5.62
Hocking	8.38	17.84	9.40	19.67	14.93	12.71
Holmes	16.26	9.58	11.67	11.78	10.13	10.10
Jackson	5.48	21.38	10.98	22.97	17.64	15.14
Jefferson	17.64	12.64	10.71	10.52	3.50	6.23
Lawrence	5.46	24.30	12.32	25.42	19.48	16.80
Mahoning	21.61	9.36	15.08	5.72	8.30	10.86
Muskingum	12.33	13.55	8.19	14.91	10.54	8.90
Noble	11.82	15.20	5.56	15.33	9.37	6.91
Perry	11.03	14.84	8.47	16.54	12.18	10.32
Stark	19.03	8.11	13.10	8.08	8.10	9.67
Tuscarawas	16.13	10.46	10.32	10.88	7.53	7.67
Vinton	6.66	19.41	9.41	20.96	15.75	13.32
Washington	10.57	17.25	3.50	17.13	10.71	7.99
Wayne	18.26	7.58	13.50	10.38	10.61	11.29
Landfill	27.50	27.50	27.50	27.50	27.50	27.50

Table 7 Estimated tons of dry FGD by-product shipped to each end use alternative from each source or power plant

Agricultural land application

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12	Total Shipped
Adams	6,718.00	0.00	0.00	0.00	0.00	0.00	6,718.00
Allen	5,091.00	0.00	0.00	0.00	0.00	0.00	5,091.00
Ashland	0.00	0.00	0.00	1,821.10	977.91	0.00	2,799.00
Ashtabula	0.00	0.00	0.00	5,599.00	0.00	0.00	5,599.00
Athens	0.00	0.00	1,258.00	0.00	0.00	0.00	1,258.00
Auglaize	8,726.00	0.00	0.00	0.00	0.00	0.00	8,726.00
Belmont	0.00	0.00	0.00	0.00	0.00	4,921.00	4,921.00
Brown	6,523.00	0.00	0.00	0.00	0.00	0.00	6,523.00
Buttler	2,021.00	0.00	0.00	0.00	0.00	0.00	2,021.00
Carroll	0.00	0.00	0.00	0.00	2,041.00	0.00	2,041.00
Champaign	4,048.00	0.00	0,00	0.00	0.00	0.00	4,048.00
Clark	3,194.00	0.00	0.00	0.00	0.00	0.00	3,194.00
Clermont	4,998.00	0.00	0.00	0.00	0.00	0.00	4,998.00
Clinton	7,002.00	0.00	0.00	0.00	0.00	0.00	7,002.00
Columbiana	0.00	0.00	0.00	0.00	6,853.00	0.00	6,853.00
Coshocton	0.00	0.00	0.00	0.00	0.00	11,259.00	11,259.00
Crawford	0.00	0.00	0.00	0.00	0.00	6,857.00	6,857.00
Cuyahoga	0.00	3,989.00	0.00	0.00	0.00	0.00	3,989.00
Darke	6,290.00	0.00	0.00	0.00	0.00	0.00	6,290.00
Defiance	0.00	11,016.00	0.00	0.00	0.00	0.00	11,016.00
Delaware	0.00	0.00	9,199.00	0.00	0.00	0.00	9,199.00
Erie	0.00	6,586.00	0.00	0.00	0.00	0.00	6,586.00
Fairfield	0.00	0.00	9,724.00	0.00	0.00	0.00	9,724.00
Fayette	5,612.00	0.00	0.00	0.00	0.00	0.00	5,612.00
Franklin	2,378.00	0.00	0.00	0.00	0.00	0.00	2,378.00
Fulton	0.00	9,404.00	0.00	0.00	0.00	0.00	9,404.00
Gallia	3,917.00	0.00	0.00	0.00	0.00	0.00	3,917.00
Geauga	0.00	0.00	0.00	313.00	0.00	0.00	313.00
Greene	4,418.00	0.00	0.00	0.00	0.00	0.00	4,418.00
Guernsey	0.00	0.00	0.00	0.00	0.00	2,827.00	2,827.00
Hamilton	638.00	0.00	0.00	0.00	0.00	0.00	638.00
Hancock	0.00	0.00	3,577.00	0.00	0.00	0.00	3,577.00
Hardin	0.00	0.00	7,457.00	0.00	0.00	0.00	7,457.00
Harris	0.00	0.00	0.00	0.00	456.00	0.00	456.00
Henry	0.00	5,745.00	0.00	0.00	0.00	0.00	5,745.00
Highland	14,993.00	0.00	0.00	0.00	0.00	0.00	14,993.00
Hocking	499.00	0.00	0.00	0.00	0.00	0.00	499.00
Holmes	0.00	0.00	0.00	0.00	0.00	3,237.00	3,237.00
Huron	0.00	0.00	0.00	16,983.00	0.00	0.00	16,983.00
Jackson	109.00	0.00	0.00	0.00	0.00	0.00	109.00
Jefferson	0.00	0.00	0.00	0.00	1,373.00	0.00	1,373.00
Knox	0.00	0.00	8,513.00	0.00	0.00	0.00	8,513.00
Lake	0.00	0.00	0.00	1,539.00	0.00	0.00	1,539.00
Lawrence	148.00	0.00	0.00	0.00	0.00	0.00	148.00
Licking	0.00	0.00	5,395.00	0.00	0.00	0.00	5,395.00
Logan	1,009.00	0.00	0.00	0.00	0.00	0.00	1,009.00
Lorain	0.00	431.00	0.00	3,812.00	0.00	0.00	4,243.00
Lucas	0.00	4,770.00	0.00	0.00	0.00	0.00	4,770.00

Table 7 (cont...)

Agricultural land application

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12	Total Shipped
Madison	712.00	0.00	0.00	0.00	0.00	0.00	712.00
Mahoning	0.00	0.00	0.00	2,438.00	0.00	0.00	2,438.00
Marion	0.00	0.00	1,903.00	0.00	0.00	0.00	1,903.00
Medina	0.00	0.00	0.00	4,879.00	0.00	0.00	4,879.00
Meigs	116.00	0.00	0.00	0.00	0.00	0.00	116.00
Mercer	2,534.00	0.00	0.00	0.00	0.00	0.00	2,534.00
Miami	2,268.00	0.00	0.00	0.00	0.00	0.00	2,268.00
Monroe	0.00	0.00	0.00	0.00	0.00	370.00	370.00
Montogmery	611.00	0.00	0.00	0.00	0.00	0.00	611.00
Morgan	0.00	0.00	628.00	0.00	0.00	0.00	628.00
Morrow	0.00	0.00	1,068.00	0.00	0.00	0.00	1,068.00
Muskingum	0.00	0.00	5,665.00	0.00	0.00	0.00	5,665.00
Noble	0.00	0.00	398.00	0.00	0.00	0.00	398.00
Ottawa	0.00	6,070.00	0.00	0.00	0.00	0.00	6,070.00
Paulding	6,170.00	0.00	0.00	0.00	0.00	0.00	6,170.00
Perry	0.00	0.00	1,241.00	0.00	0.00	0.00	1,241.00
Pickaway	2,946.00	0.00	0.00	0.00	0.00	0.00	2,946.00
Pike	5,062.00	0.00	0.00	0.00	0.00	0.00	5,062.00
Portage	0.00	0.00	0.00	3,483.00	0.00	0.00	3,483.00
Preble	2,660.00	0.00	0.00	0.00	0.00	0.00	2,660.00
Putnam	0.00	0.00	2,501.00	0.00	0.00	0.00	2,501.00
Richland	0.00	0.00	0.00	0.00	0.00	4,119.00	4,119.00
Ross	1,630.00	0.00	0.00	0.00	0.00	0.00	1,630.00
Sandusky	0.00	3,019.00	0.00	0.00	0.00	0.00	3,019.00
Scioto	454.00	0.00	0.00	0.00	0.00	0.00	454.00
Seneca	0.00	5,542.00	0.00	0.00	0.00	0.00	5,542.00
Shelby	1,962.00	0.00	0.00	0.00	0.00	0.00	1,962.00
Stark	0.00	0.00	0.00	0.00	2,381.00	0.00	2,381.00
Summit	0.00	0.00	0.00	1,543.00	0.00	0.00	1,543.00
Trumbull	0.00	0.00	0.00	3,846.00	0.00	0.00	3,846.00
Tuscarawas	0.00	0.00	0.00	0.00	2,695.00	0.00	2,695.00
Union	1,948.00	0.00	0.00	0.00	0.00	0.00	1,948.00
Van Wert	1,115.00	0.00	0.00	0.00	0.00	0.00	1,115.00
Vinton	153.00	0.00	0.00	0.00	0.00	0.00	153.00
Warren	1,720.00	0.00	0.00	0.00	0.00	0.00	1,720.00
Washington	0.00	0.00	1,963.00	0.00	0.00	0.00	1,963.00
Wayne	0.00	0.00	0.00	0.00	11,462.00	0.00	11,462.00
Williams	0.00	6,405.00	0.00	0.00	0.00	0.00	6,405.00
Wood	0.00	7,023.00	0.00	0.00	0.00	0.00	7,023.00
Wyandot	0.00	0.00	0.00	0.00	0.00	5,724.00	5,724.00

Table 7 (cont...)

Coal surface mine reclamation and landfill alternative

	Mountaineer S25	Edgewater S11	Muskingum S16	Niles S9	Sammis S8	Burger S12	Total Shipped
Athens	0.00	0.00	311.64	0.00	0.00	0.00	311.64
Belmont	0.00	0.00	0.00	0.00	0.00	5,565.50	5,565.50
Carroll	0.00	0.00	0.00	0.00	1,636.60	0.00	1,636.60
Columbiana	0.00	0.00	0.00	0.00	1,268.10	0.00	1,268.10
Coshocton	0.00	0.00	0.00	0.00	0.00	3,904.10	3,904.10
Guernsey	0.00	0.00	0.00	0.00	0.00	286.97	286.97
Harrison	0.00	0.00	0.00	0.00	4,261.70	0.00	4,261.70
Hancock	262.00	0.00	0.00	0.00	0.00	0.00	262.00
Holmes	0.00	0.00	0.00	0.00	0.00	933.45	933.45
Jackson	2,048.80	0.00	0.00	0.00	0.00	0.00	2,048.80
Jefferson	0.00	0.00	0.00	0.00	3,953.70	0.00	3,953.70
Lawrence	54.75	0.00	0.00	0.00	0.00	0.00	54.75
Mahoning	0.00	0.00	0.00	408.91	0.00	0.00	408.91
Muskingum	0.00	0.00	1,857.90	0.00	0.00	0.00	1,857.90
Noble	0.00	0.00	6,917.10	0.00	0.00	0.00	6,917.10
Perry	0.00	0.00	841.02	0.00	0.00	0.00	841.02
Stark	0.00	0.00	0.00	0.00	403.88	0.00	403.88
Tuscarawas	0.00	0.00	0.00	0.00	4,342.80	0.00	4,342.80
Vinton	3,047.40	0.00	0.00	0.00	0.00	0.00	3,047.40
Washington	0.00	0.00	134.92	0.00	0.00	0.00	134.92
Wayne	0.00	0.00	0.00	0.00	65.85	0.00	65.85
Landfill	757,524.00	0.00	869,447.40	0.00	1,689,128.00	386,656.00	3,702,755.40

Summary of shipment estimates

	Mountaineer	Edgewater	Muskingum	Niles	Sammis	Burger	Total Shipped
Total Ag.	120,393.00	70,000.00	60,490.00	46,256.10	37,823.00	39,314.00	374,276.01
Total Reclaim	5,412.95	0.00	10,062.58	408.91	15,932.63	10,690.02	42,507.09
Total Landfill	757,524.05	0.00	869,447.42	0.00	1,679,544.37	386,655.98	3,693,171.82
Total	883,330.00	70,000.00	940,000.00	46,665.01	1,733,300.00	436,660.00	4,109,955.01
% Ag.	13.63%	100.00%	6.44%	99.12%	2.18%	9.00%	8.87%
% Reclaim	0.61%	0.00%	1.07%	0.88%	0.92%	2.45%	1.03%
% Landfill	85.76%	0.00%	92.49%	0.00%	96.90%	88.55%	89.86%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Figure 1 Percentage of total FGD by-product produced and distributed among the three end use alternatives selected by plant

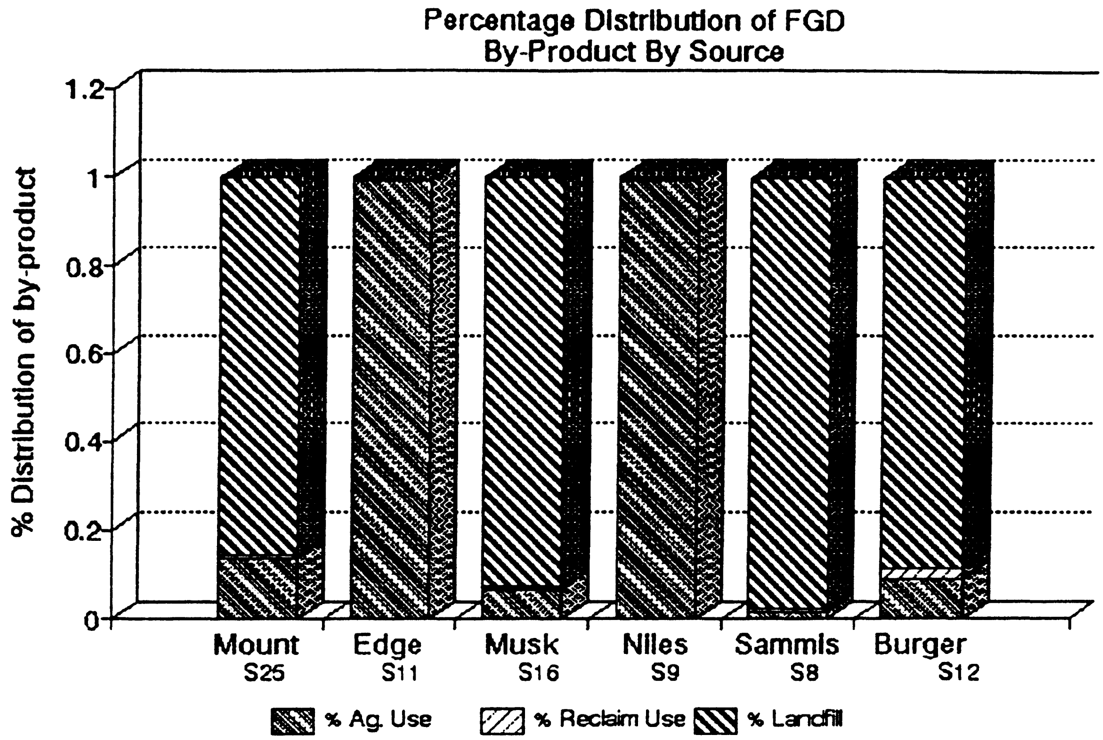


Figure 1 shows the percentage distribution of dry FGD by-product produced at six Ohio power plants among the three end use alternatives stated. Notice that at five of the power plants (Mountainer (Mount), Muskingum (Musk), Sammis, and Burger) at least 85 percent of the dry FGD by-product is landfilled. At two of the six power plants (Edgewater (Edge) and Niles) nearly all by-product material is applied to agricultural land (100%). Surface coal mine reclamation accounts for negligible quantities of total FGD by-product produced (1.03%) from all six power plants.

Figure 2 Quantity of FGD by-product produced and distributed among the three stated end use alternatives by selected Ohio power plant.

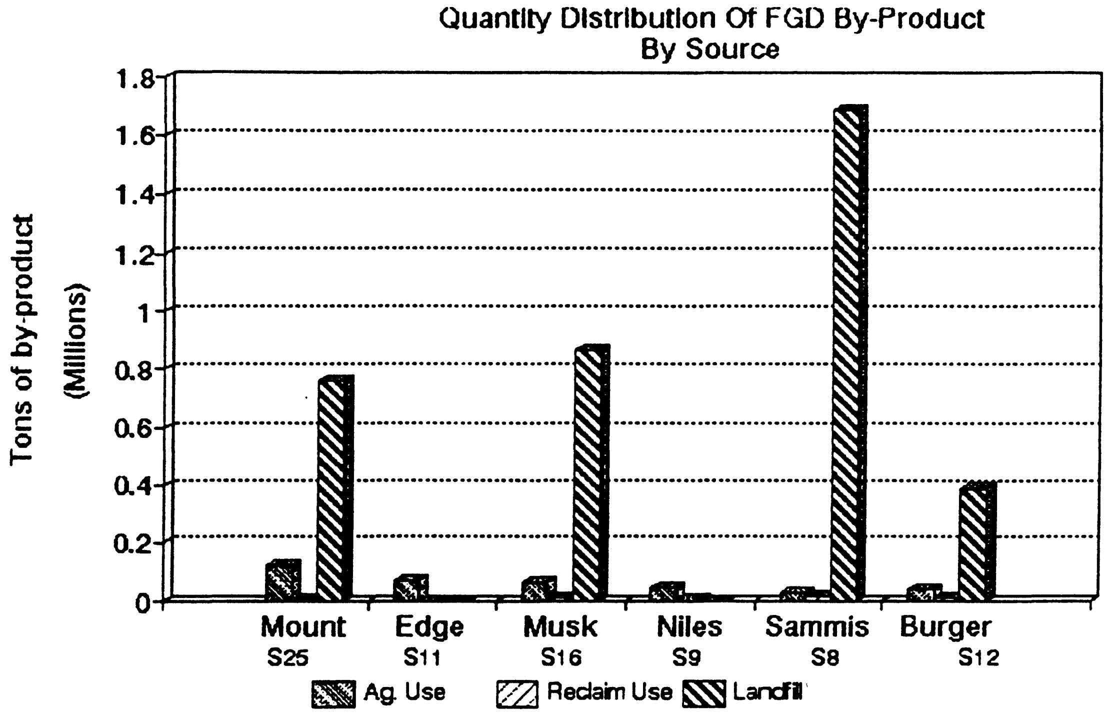


Figure 2 shows the quantity of dry FGD by-product distributed among the three end use alternatives from each source. Of the total quantity of dry FGD by-product produced, assuming a 25% adoption rate, little dry FGD by-product is used in agriculture (8.87%) or surface coal mine reclamation (1.03%), but is landfilled (90.1%). Suggesting that (a) a higher adoption rate among farmers and surface mine operators would reduce the quantity landfilled, (b) the amount of dry FGD by-product produced greatly exceeds current quantities demanded or (c) additional end uses for the by-product must be found. Based upon the estimated total output of dry FGD by-product from these six power plants to be 4.1 million tons annually, current agricultural land application and coal surface mine reclamation use at 100% adoption is estimated to be about 1.7 million tons per year. This suggests that 2-3 million tons of dry FGD by-product must be either landfilled or some alternative use must be found assuming complete substitution of dry FGD by-product for agricultural and surface coal mine reclamation.

Figure 3 Quartiled distribution of Agricultural land application of FGD by-product assuming a 25% rate of adoption

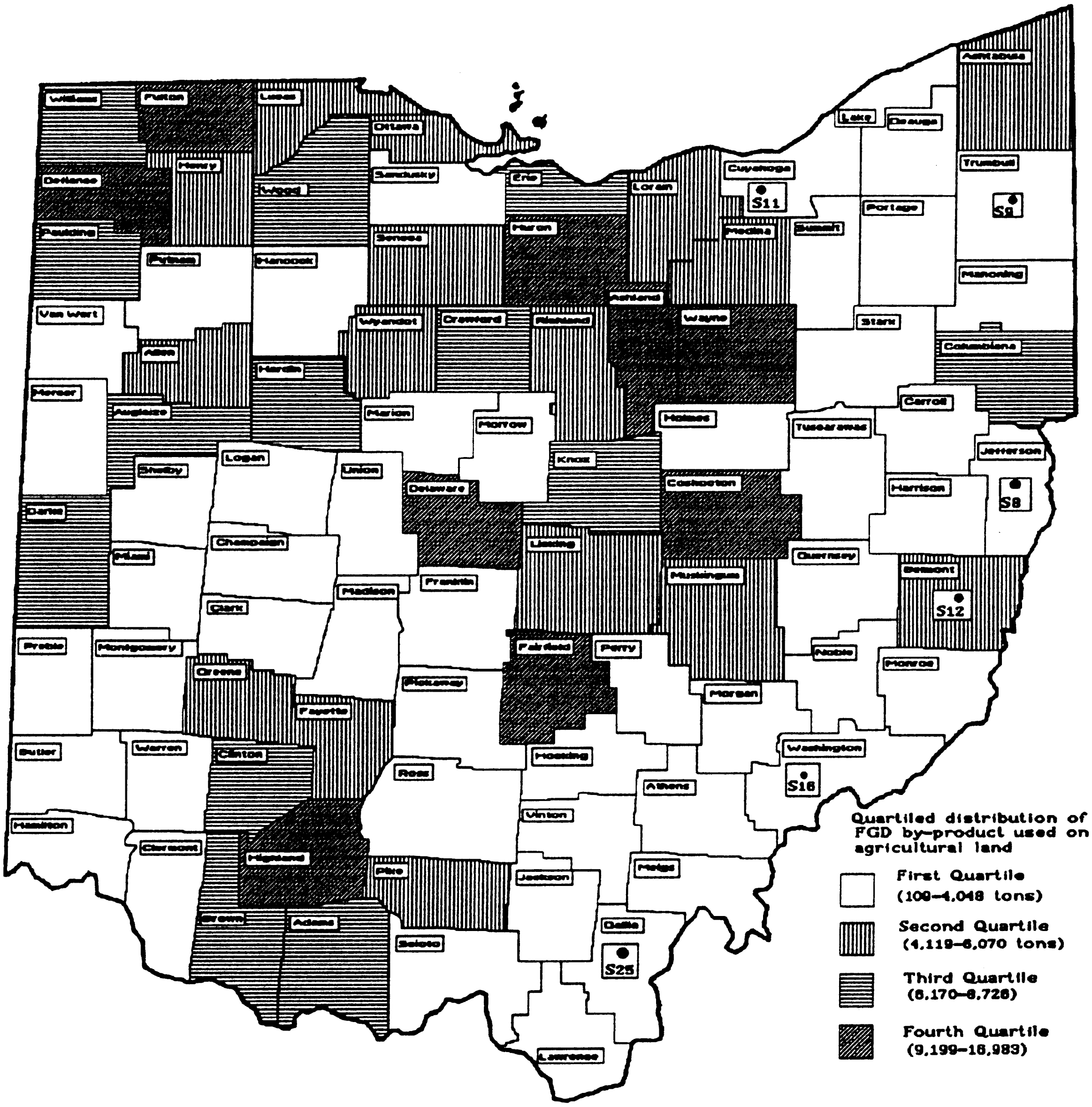


Figure 3 shows the distribution of dry FGD by-product as a substitute for agricultural lime from these six power plants. Quartiles were developed based upon the quantity of dry FGD by-product estimated to be shipped to each Ohio county for agricultural land application. The first quartile, or counties using the lowest 25% of dry FGD by-product, are not shaded. Counties with shading indicate the second lowest 25% of agricultural use through the largest 25%.

Figure 4 Coal surface mine reclamation use of dry FGD by-product assuming a 25% adoption level.

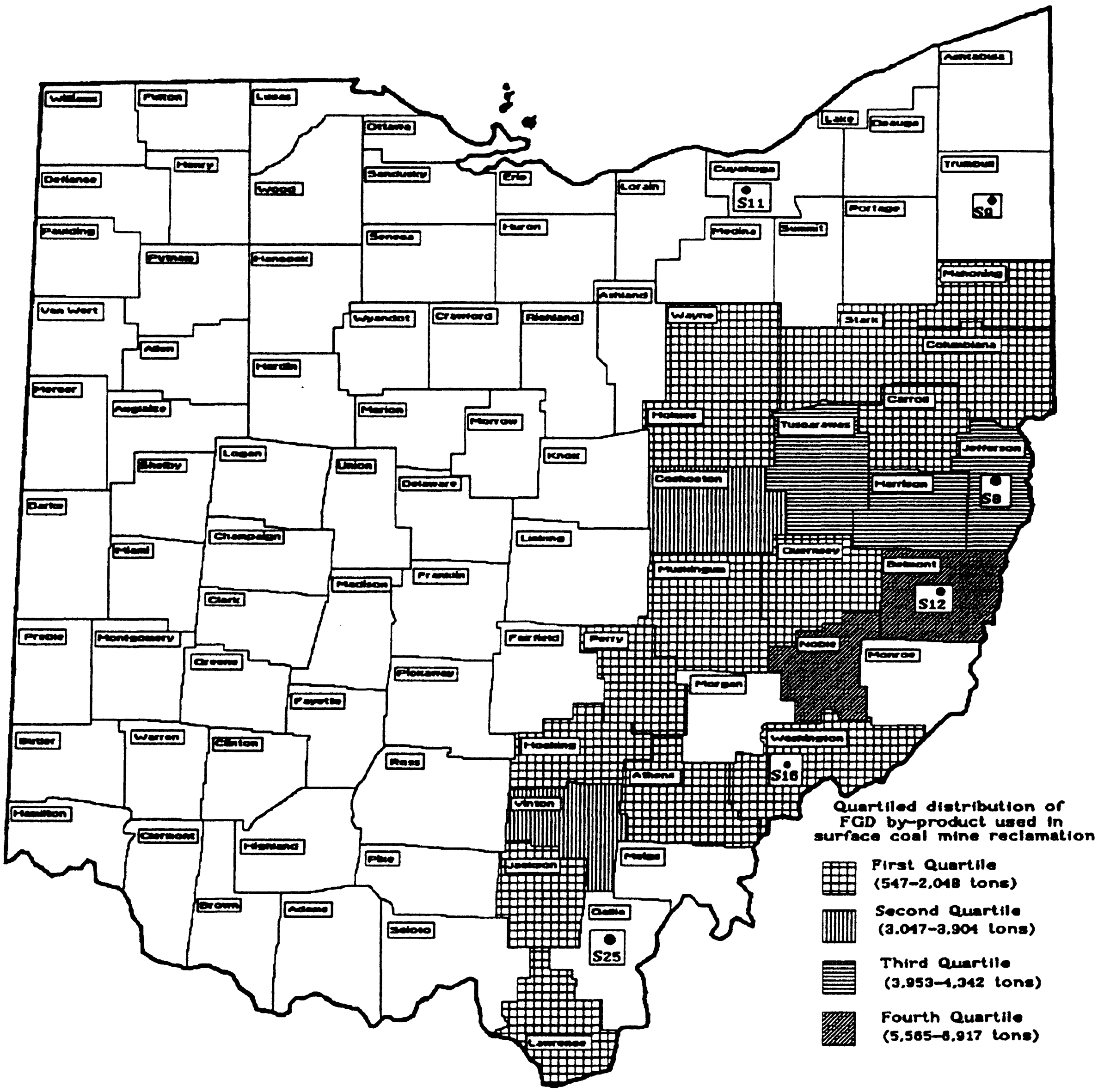
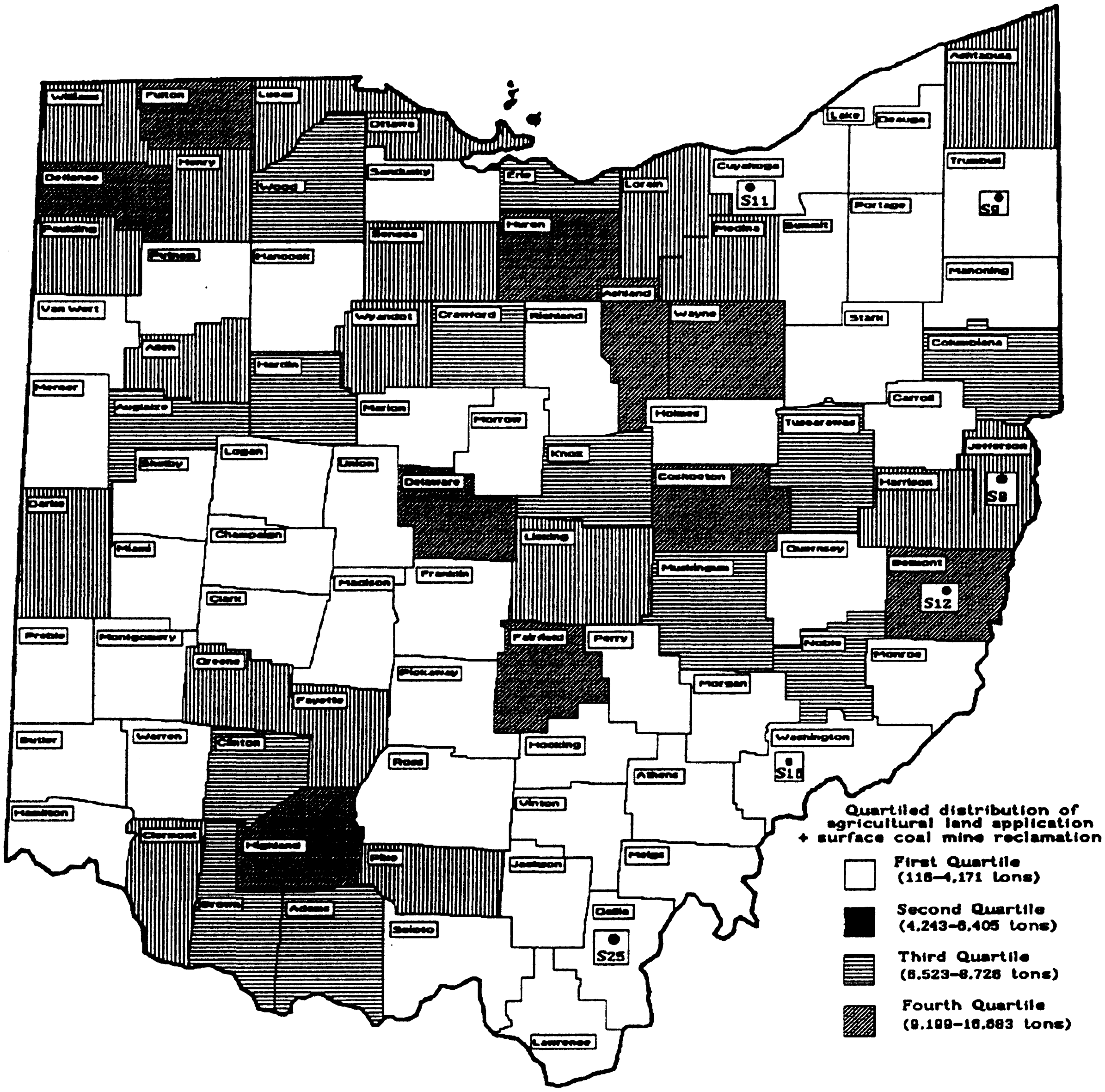


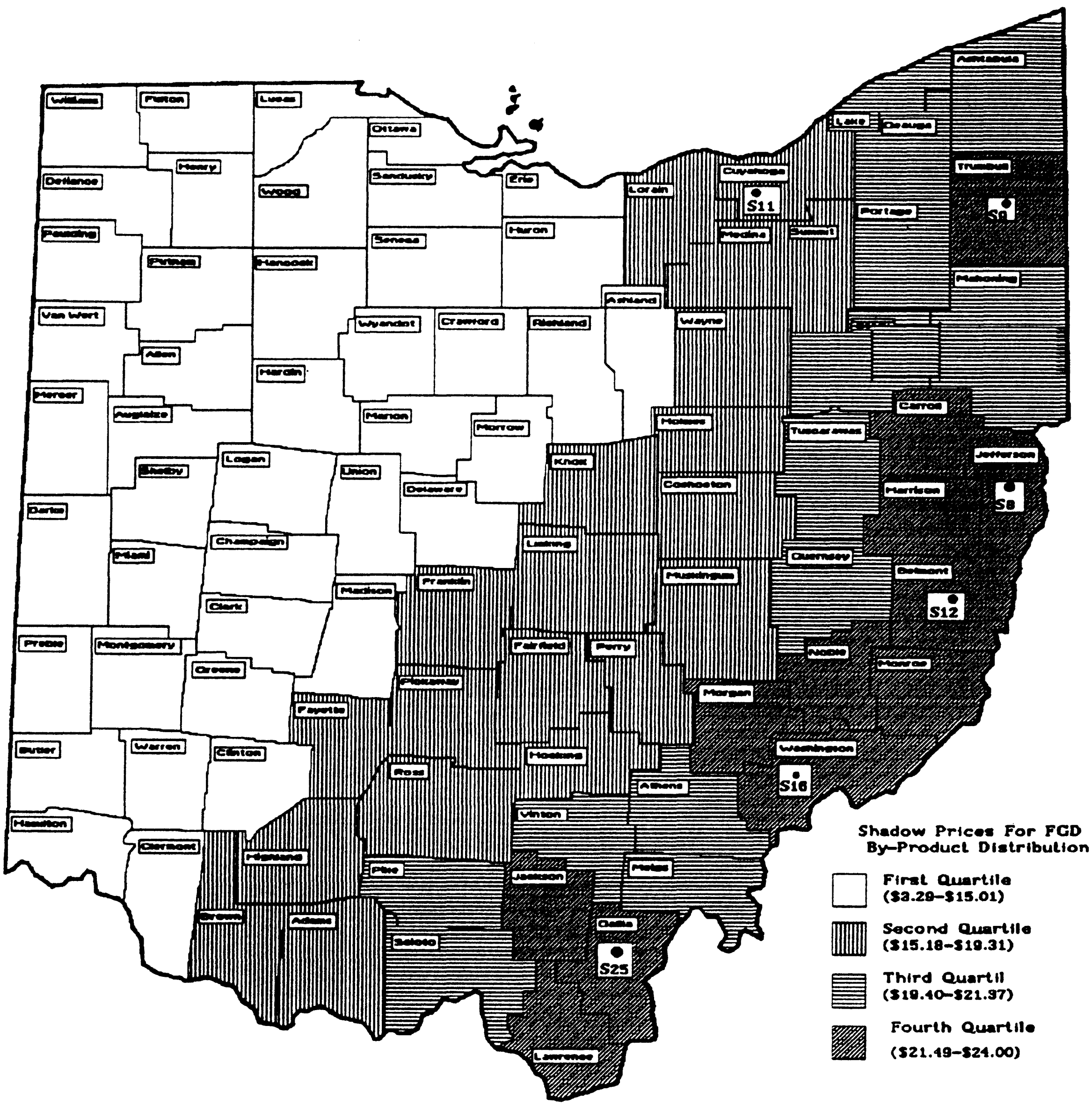
Figure 4 shows a quartiled distribution of dry FGD by-product for coal surface mine reclamation. Since only 21 counties have coal surface mine activity, all quartiles are shaded, and represent the lowest to highest quantities of dry FGD by-product used. Again, the quantity of dry FGD by-product associated with a given quartile are in hundreds of tons, and represent one-fourth of the total dry FGD by-product shipped for coal surface mine reclamation from the six power plants selected.

Figure 5 Agricultural land application and coal surface mine reclamation use of dry FGD by-product assuming a 25% level of adoption



The final geographic representation of dry FGD by-product distribution shows both agricultural land application and coal surface mine reclamation, or a quartiled total distribution of dry FGD by-product (Figure 5). Each quartile represents one-fourth of the dry FGD by-product used as an amendment to land (both agricultural and coal surface mine reclamation lands). For example, four counties (Belmont, Coshocton, Noble, and Tuscarawas) within the fourth quartile receive one-fourth of the total dry FGD by-product applied to land.

Figure 6 Shadow prices for land application or electric utilities estimated cost savings from land application versus landfilling dry FGD by-product



The final objective of this research was to estimate the shadow price associated with each demand or destination node. Shadow prices are imputed prices which reflect the increase/decrease in total costs if one additional unit of product were available. In this case, the additional unit is the use of one additional ton of dry FGD by-product on agricultural land or in coal surface mine reclamation. Shadow prices for dry FGD by-product are calculated as the difference between landfilling (non-binding constraint) and agricultural land application or coal surface mine reclamation options (both binding constraints). It would be expected that as the distance from the power plant increases, the cost to move this by-product also increases, therefore the imputed value or shadow price for binding end use options farther from the source or power plant would be lower. That is, the difference between landfilling and shipping dry FGD by-product material greater distances would be smaller. Thus, counties located farther from dry FGD by-product sources would have lower shadow prices or lower cost savings to the utility companies than would land application sites closer in proximity to the power plant. Figure 6 shows the shadow price associated with the distribution of dry FGD by-product to each Ohio county.

Another interpretation of these shadow prices is the amount the power plant would be willing to pay for the disposal of an additional ton of by-product in each end use alternative. For example, Figure 6 shows Williams county in the first quartile or having a shadow price between $3.29-15.01 per unit. The calculated shadow price for Williams county is $3.29 per ton, suggesting the power plant would be willing to pay the farmer up to $3.29 to use an additional ton of dry FGD by-product as opposed to landfilling it at a cost of $27.50 per ton.

Conclusion

Under Title IV of the 1990 Clean Air Act electric power generating plants will be required to reduce SO_2 and NO_x emissions by about 40 percent no later than the year 2000. These emission standards are most significant for power plants which burn coal, particularly high sulfur coal, as an energy source. In order to achieve compliance with these mandates, power plants will be have to reduce demand for electricity there by reduce the quantity of coal burned, use fuels lower in sulfur, purchase emission allowances, retrofit existing power plants with clean air technology, or a combination of the above. Currently, the only clean air technology available to existing power plants is Flue Gas Desulferization (FGD) technology. EPA has estimated that this technology can reduce SO_2 by as much as 95%. However, dry FGD technology creates another environmental concern--disposal of the used sorbent. Based upon current coal consumption estimates, Ohio could potentially produce nearly 4 million tons of dry FGD by-product (used sorbent) annually from six Ohio power plants. The objectives of this research were to estimate a least cost disposal model for the movement of this by-product to various geographic locations throughout Ohio and for use as a soil amendment for agricultural land, coal surface mine reclamation, and landfilling. In doing so, total disposal costs and quantities were derived as well as shadow prices for each county (demand node) identified.

This analysis uses one scenario for future dry FGD by-product distribution and uses. Others are plausible and easily analyzed by this model. The linear transportation model estimated suggests that the least cost disposal of dry FGD by-product would cost $107 million to dispose of 4.1 million tons of dry FGD by-product material annually. This is equivalent to average cost of $26.10 per ton of dry FGD produced. The two end use alternatives currently identified are dry FGD by-product use as soil amendments on agricultural land and coal surface mine reclamation, in addition to landfilling. Of these three options, landfilling accounts for about 90 percent of the total by-product produced, while agricultural and surface coal mine reclamation account for about 8.87% and 1.03% respectively. Therefore, on average land application of dry FGD by-product represents a savings of $1.40 ($27.50 (landfilling) - $26.10 (average cost of disposal per ton)). However, at the margin (one additional ton) land application represents a cost savings of about $14.81 per ton. That is, electric power plants can reduce total cost of dry FGD by-product disposal by $14.81 per ton through land application rather than landfilling.

Agricultural use of dry FGD by-product is spread widely over the state. Agricultural use is concentrated in the western two-thirds of Ohio, while coal surface mine reclamation use is important in the eastern one-third of the state. Yet, of the alternative disposal options identified, the vast majority (3.8 million tons) of dry FGD by-product is landfilled, followed by agricultural land application (374,276 tons) and then coal surface mine reclamation (42,507 tons). Given these end use alternatives, more FGD by-product will be buried in landfills than will be used in other alternatives combined. However, electric utilities have an enormous economic incentive to supply dry FGD by-product to land. They could pay farmers substantial amounts and save landfilling costs.

Sources

EPA Journal. 1986. "ACID RAIN An EPA Journal Special Supplement" Vol. 12, Number 5, June/July. Office of Public Affairs, Washington, DC.

Helme, Ned and Chris Neme. 1991. "Acid Rain: The Problem," EPA Journal. Vol. 17, Number 1, Jan/Feb. Office of Communication and Public Affairs.

Claussen, Eileen. 1991 "Acid Rain: The Strategy," EPA Journal. Vol. 17, Number 1, Jan/Feb. Office of Communication and Public Affairs.